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ABSTRACT

Heating is an undesirable effect of the compression process at least as far as compressors are concerned and heat transfer is nature's way of driving systems towards stability. This has not only provided food for thought for researchers trying to understand its influence and quantify its effects, but also challenged designers to mitigate its impact and develop safe and efficient designs. Also, just as any other unwanted phenomenon would spur curiosity and inventiveness, this has led to the development of a host of new materials both metallic as well as non-metallic to withstand the vagaries of high temperatures, in addition to the toxic environment present in many gas compressors used in pumping and process industries. This paper is an attempt to present some of the problems created by this unwanted phenomenon, review the contributions of some of the past investigators, and kindle more interest for furthering the advancement of compressor technology.

INTRODUCTION

Until recently, heat transfer in reciprocating compressors had assumed a back burner role. The recent trend in energy consciousness has rekindled interest and generated considerable debate and contradictory opinions about the extent of influence of heat transfer on compressor performance. Heat transfer does not just affect the performance but also the design, operation and reliability of compressors.

One of the main limitations in the design of compact single stage compression systems is the inability to control the large temperatures generated during the compression process. Hence the need for multi staging.

Temperature also becomes a defining parameter in the operation of many compressors. In many cases, the operational pressure ratio needs to be limited depending on the inlet temperature (which is beyond the control of the user), in order to keep the discharge temperature within safe limits. Also, unloaded operation, which results in higher than normal temperatures, may be forbidden because of temperature limitations.

From the reliability point of view, temperature affects many of the material properties in addition to dimensional stability and integrity of the component itself.

In as far as compressor performance is concerned, it is well known that heating and cooling of the gas are unavoidable events associated with compression and expansion inside reciprocating compressor cylinders. An obvious result of this is the transfer of heat from and to the gas which also occurs in an unsteady manner. It has both advantages as well as disadvantages. In spite of its complexity, the phenomenon of heat transfer has attracted the attention of many more investigators in the area of internal combustion engine than compressors. This might be partly due to the dominant role played by heat transfer in an engine, while converting the heat content of the fuel into mechanical energy. However, as compressor efficiencies are approaching their limits and energy deficiencies have started looming on the horizon, designers have started searching for energy savings at whatever cost. This is driving researchers to take a second look at the effect of heat transfer on the performance of compressors. The early stages of such effort were clouded with conflicts of opinion between different groups and it is only since the 80's, that the importance of the influence of heat transfer on compressor performance has been recognized. At least as far as reciprocating compressors are concerned, the most important effect appears to be in heating the suction gas which has a direct effect in reducing volumetric efficiency and an indirect effect in increasing the HP requirement. Further, discharge gas cooling is important at least in high pressure ratio reciprocating compressors and vacuum pumps in reducing the discharge temperature.

The mechanism of heat transfer inside the cylinder is quite complex to handle completely, either theoretically or experimentally, and hence has attracted the attention of both types of workers. On the theoretical front, in addition to the basic research for understanding the phenomenon of unsteady heat transfer inside compressor cylinders , some in-cylinder heat transfer correlations have been developed for use in modeling in order to account for heat transfer effects on compressor performance. In the area of experimentation, improvements in sensor and instrumentation technology have helped in making simultaneous measurements of in-cylinder temperature, pressure and heat transfer rates. Further, there have been some attempts to incorporate the present understanding of the phenomenon of heat transfer in compressor simulation models in order to transfer the knowledge gained to designers for analyzing and designing better machines. However, the progress in this direction is still in its infancy due to the many gaps which exist in the understanding of the mechanisms and its modeling as well as the difficulty in making detailed measurements to validate such models. The problem is compounded by the fact that the compressors have complex geometries which defy universal approaches to modeling even with subtle variations.

This paper attempts to give a birds eye view of the problems associated with the phenomenon of heat transfer in reciprocating compressors and the efforts of some of the past investigators in unraveling the mystery of its influence and contributing to the design of better compressors. The paper contains a limited bibliography. Only investigations directly related to the discussion in the paper are referenced. The main aim of this paper is to kindle further interest in this topic and hence the author does not claim to have done even partial justice in making a thorough and exhaustive review.

ANALYTICAL MODELING

Mathematical modeling of the dynamic processes in a compressor involves a knowledge of the various forms of energy exchange occurring in the system. Heat transfer to and from the gas is one such. In spite of some researchers' (see Qvale et al., 1972) predictions of large impact of heat transfer on compressor performance, and their call for investigations to study its influence, until recently, very little attention was paid to heat transfer modeling and assessment of its effects. It was partly because of the lack of consensus about the seriousness of its impact and partly due to its complexity. Recent works by the author (1992b, 1993a,b) as well as by Gerlach and Berry (1989) have indicated a significant influence on compressor performance.

"Suction gas heating" and "discharge gas cooling" are two important mechanisms which determine the extent of influence of heat transfer on compressor performance. Heat transfer to the suction gas can be assumed to occur in various stages through all the three modes. Before the gas enters the cylinder, heating takes place in the suction pipes by radiation. Conductive and convective heating occurs as the gas flows through the cylinder and valve passages. Finally, inside the cylinder itself, indirect heating and regenerative heating impart some more heat to the suction gas. Indirect heating here refers to the temperature increase of the gas, due to the pressure increase during the suction stroke, which occurs as a consequence of the pressure drop across the suction valve. In regenerative heating, as the name itself implies, the needed heat is generated inside the cylinder and transferred to the wall during a part of the compression and the complete discharge stroke. This heat is given back to the gas during the suction and a large part of the expansion stroke. Although the process of exchange of heat between the gas and the cylinder is taking place continuously, there is no net exchange of heat between the compressor system and its surroundings and hence it could be called an "adiabatic system" in the absence of cylinder cooling. In a way similar to suction gas heating outside the cylinder, the regenerative heating of the suction gas also adversely affects the capacity and power economy of the compressor.

In the area of heat transfer modeling, refrigeration compressors have drawn the most attention, perhaps due to the sheer demand for such machines. Scheideman et al. (1978), Meyer and Thompson (1990), Hiller and Glicksman (1976), and Prakash & Singh (1974) have incorporated heat transfer models in their overall simulation of compressor performance. Only Prakash and Singh have considered regenerative heat transfer inside the compressor cylinder in addition to conductive and convective heat transfer across suction and discharge passages. Pandeya and Soedel (1978) derived a simple relationship for the change in mass flow rate expressed as a function of the magnitude of suction gas heating using thermodynamic principles. Brok et al. (1980) used two techniques to predict the influence of heat transfer on volumetric efficiency and horsepower requirement for an adiabatic compressor case as well as the case with cylinder cooling. They concluded that heat transfer effects were not so dominant as described by some earlier investigators and gave a value of 2.5% as the maximum impact on volumetric efficiency or HP requirement for the worst operating condition for a compressor with a pressure ratio of 4.15. They further concluded that designing a compressor to prevent heat transfer effects or developing a model to include heat transfer effects as a part of overall simulation is not worthwhile.

Gerlach and Berry (1989) have reported a systematic study of heat transfer effects in a reciprocating compressor. They divide it in to direct and indirect heating effects. They used a wall heat transfer correlation similar to that of Adair et al. (1972) to model regenerative heating in their overall compressor simulation program and arrived at heat transfer loss estimates by force fitting measured discharge temperature data. They also measured the capacity loss due to heat transfer by monitoring the capacity right from the instant the compressor was started until the system attained a steady state. They noticed a capacity loss as high as 10%. Using their mathematical simulation, they also studied the effect of several operating parameters like speed, pressure ratio, suction pressure, size of cylinder, etc., on heat transfer loss. Their results indicate that heat transfer plays a very important role in achieving efficient operation of reciprocating compressors. Gerlach and Berry's conclusion of a large impact of heat transfer on volumetric efficiency was confirmed by the author (see Shiva Prasad, 1992b, 1993a , b) in his detailed investigations for developing a quick and direct analytical method for estimating the effect of suction gas heating on capacity loss. Using the close analogy between suction gas heating and discharge gas cooling, the author (see Shiva Prasad, 1997) recently developed a method for calculating discharge gas temperatures in high pressure ratio reciprocating compressors and vacuum pumps. Just as in the case of suction gas heating, the state of the gas inside the cylinder was computed over the complete cycle by using isentropic relations for the compression and expansion strokes, and the one dimensional conservation equations for mass, momentum and energy along with the equation of state for the suction and discharge strokes.

The work of modeling heat transfer inside the cylinder itself was initially focussed on engines and started with the early dimensional models formulated by Nusselt (1923) and Eichelberg (1939). Those models had inherent scaling problems and hence gradually gave way to dimensionless models proposed by Taylor and Taylor (1961), Annand (1963) and Woschni (1967). The dimensionless models were mere adaptations of the Reynlods number - Nusselts number formulations commonly used in pipe flows and hence lacked representation of the physics of flow inside cylinders. Just as in many other fluid dynamic configurations, the lack of input from the parameters controlling the unsteadiness, the turbulence and the boundary layer inside the cylinder resulted in models with poor resolution in time, space and even over design variations. There have been recent attempts by many investigators (again with reference to engines) like Borgnakke et al. (1980), Blumberg et al. (1979), Morel and Keribar (1985) and others to use mathematical models of the conservation equations for extracting the proper velocity and length scales of fluid motions and incorporating them in dimensionless heat transfer models. However, such detailed modeling approach would involve a large computer time and effort and may not be suitable for quick performance prediction procedures. Other than a few investigations by Keribar and Morel (1988), Chong and Watson (1980), etc., they have also not been actively pursued in the compressor field so far. Even in terms of the simpler models, Adair et al. (1972) was perhaps one of the few to adapt a dimensionless model to a compressor by using his experimental data.

On a more fundamental basis, several investigators have questioned the applicability of the simple Newton's law of cooling to a basically oscillating flow with large amplitude pressure variations. Pfriem (1943) was the first to recognize the possible existence of a phase difference between the heat flux and the temperature gradient for such a flow. He solved a simplified form of the one-dimensional energy equation and derived an expression for the complex Nusselt number, which could account for this phase difference. This was later followed by Lee (1983), who included the effect of turbulence by introducing a turbulent thermal diffusivity in to his definition of the Peclet number. Subsequently, Kornhauser and Smith (1988) revised the complex Nusselt number model to cover the low and high ends of the Peclet number range, followed by Yagyu and Smith (1991), who extended the model to cover all the harmonics of a practical, nonsinusoidal compressor flow. Recently, Catto and Prata (1997) used a finite volume technique to numerically integrate the conservation equations for mass, momentum and energy inside a gas spring to compute the instantaneous heat flux which correlated with the complex Nusselt number model of Kornhauser and Smith.

As discussed above, there have been many investigations concerning development of heat transfer correlations for the complex unsteady flow which exists inside the cylinders of reciprocating compressors. As far as cylinder passages, valve chambers and passages are concerned, virtually no correlation is available. Although the flow could be considered as steady and hence appear simpler, the complexity of practical geometries excludes direct applicability of available standard correlations developed for laboratory type flows. Experimental data indicate heat transfer coefficients much larger than obtained from correlations for standard geometries. This can justifiably be attributed to a number of mixing generation mechanisms like sharp bends, complex geometries, geometry variations, surface roughness, etc., which tend to augment heat transfer compared to smooth pipes used while arriving at standard heat transfer correlations. This underlines the inadequacy of standard heat transfer correlations for application to practical, complex geometries as found in compressors, and the need for further work in this area.

Cylinder wall heat transfer correlations, both inside as well as outside the cylinder are also required for calculating the distribution of temperature through out the wall. This in turn is required for estimating the distribution of total stress in the material of the wall for ensuring structural integrity. Here again the heat conduction part of the calculation using finite difference or finite element procedures are well established and even some commercial softwares can handle the problem. However, the gas side and the water side film heat transfer correlations remain as stumbling blocks. Keribar and Morel (1988) have extended their in-cylinder heat transfer modeling based on solution of conservation equations approach to this conjugate heat transfer problem by coupling the conduction and convection calculations and developed methods of calculating cylinder wall temperature distributions.

PROGRESS IN EXPERIMENTATION

Any detailed modeling of the heat transfer process would require a detailed knowledge of the temperature variations resolved to temporal scales at least as fine as the finest generated by the dynamics of the valves and their interaction with the cylinder and piping. Optical sensing techniques using laser induced fluorescence have an advantage of being a noncontact type, while providing a faster response also. However, they are not easily adaptable to measurement inside a compressor and also need sophisticated instrumentation. Hence, thermocouples and R.T.Ds. are the most commonly used sensors for gas and wall temperature measurement in a compressor. Sensor technology has advanced rapidly enough to provide response times as fast as 10 μsec for surface temperature measurement (eroding thermocouples made from metallic whiskers), and 1 msec for gas temperature measurement (bare wire thermocouples). Currently, by combining infrared sensors with thermocouples, infrared thermocouples are being developed for noncontact surface temperature measurement, which after improvement in their response times, could become useful for measuring temperatures of moving parts like pistons and valves.

On the experimental side, as reported in the previous section, Brok et al. (1980), and Gerlach and Berry (1989) as well as Jacobs (1976) have done some heat transfer measurements in order to estimate the effect of suction gas heating on volumetric efficiency. Measurement of temperature and heat flux inside the cylinder of a reciprocating compressor is not an easy task. It is perhaps this reason, as well as the lack of instrumentation, which constrained earlier model developers (with the exception of Brok et al.) to validate their simulations by using only the P-V cards to compare with experimental pressure - time traces. Heat transfer has only an indirect effect on the P-V card and hence such validations would not be a good test for the heat transfer models. This necessitates measurement of in-cylinder temperature - time traces for developing such models. Several investigators including the author (see Shiva Prasad, 1992a, b), Lee and Smith (1980), Hanjalic and Stošić(1978), etc. have attempted to make such measurements in order to further understand and model the in-cylinder regenerative heat transfer process. Although these measurements were able to resolve the time scales enough to identify the phase differences between near wall temperature gradients and heat transfer rates, the spatial resolution was not enough to resolve the length scales. Hence more work needs to be done in order to help develop as well as validate in-cylinder heat transfer models. Also, as stated in the previous section, temperature and heat transfer measurements are required in the cylinder passages as well as valve chambers and passages for developing heat transfer correlations.

COMPRESSOR DEVELOPMENT ISSUES

One can easily visualize what the direct impact of heat transfer would be on material temperatures. Large material temperatures could be attributed to large discharge temperatures. This is indeed the case in vacuum pumps and other high pressure ratio reciprocating compressors operating at pressure ratios of 30 - 40 , resulting in isentropic temperatures as high as 1200° F at the end of the compression stroke. Even in low pressure ratio compressors, suction gas heating, if not kept under control would lead to higher inlet temperatures which gets amplified to large discharge temperatures. Suction gas heating occurs in many ways. Unloading one of the ends will result in pushing the gas back and forth through the unloaded end many times which will tend to heat up the gas. This hot gas will mix with the fresh charge and eventually enter the loaded end at a temperature much higher than the inlet temperature in the suction piping. Since the suction gas entering the loaded end has become hotter, the discharge temperature will be much higher than for a cylinder with both ends loaded. The extent of suction gas heating in this case depends on various factors like speed of the compressor, which determines the residence time of the gas entering the unloaded end in the suction passage; ratio of the swept volume to the cylinder suction passage volume, which determines the amount of gas pushed from the unloaded end which enters the loaded end during the subsequent stroke; number and location of the suction ports with reference to the inlet nozzle, which determines the flow pattern into the loaded end, etc. In addition to unloading an end, suction gas heating could also be caused by leakage past piston rings and valves, which is of serious concern in high pressure ratio compressors, and frictional heating near the rider bands and packing rings, which are of main concern in nonlubricated, high speed compressors.

Although there is no disagreement about the harmful effects of such high discharge gas temperatures, there is still some skepticism in the compressor community about the extent of its impact on performance. Such skeptics would perhaps be satisfied by just getting rid of this heat by providing efficient cooling or developing materials which could withstand such high temperatures. This has spurred lot of research in material technology to develop materials particularly for valves, rider bands, piston and packing rings, etc. Research is also being done to develop new coatings for piston rods, cylinder liners, etc., to reduce the wear and withstand the high temperatures. Ideally, from the suction gas heating point of view, one would like to have materials/coatings for suction passages and valves which would behave as perfect insulators. Cylinder liners and other internal cylinder boundaries should act like diodes and transport heat only outwards during parts of the cycle when the gas inside becomes much hotter than the cylinder walls. In fact, development in material technology and smart materials which can actively adjust to the environment is occurring at such a fast pace, the author can easily envision development of materials with sandwiched spaces between them, which can be filled with a highly conducting or insulating fluid using active control, depending on the temperature gradient between the gas and the cylinder wall, which can function like diodes. The high temperature environment in compressors has also generated the need and interest for developing lubricants for withstanding such high temperatures inside the cylinders of lubricated compressors. If external cooling is to be provided, particularly in non lubricated cylinders, the mechanical aspect of design also becomes complex in many cases because of the complexity of the cooling passages. Further, in multistage compressors, intercooling becomes a necessity in many cases and in all compression systems, after cooling has to be done to meet the user's requirements.

Even from the reliability point of view, high temperatures cause serious concern. For example, impact strength of a valve plate or the sealing effectiveness of a piston or packing ring depends on the temperature. Cylinder lubricants may not just lose their viscosity, but also may break up leading to deposition on valve plates and passages causing inefficient operation or even failure. Any such deposition of a lubricant, or refrigerant in refrigeration compressors, or water / liquid droplets / slugs in compressors operating at relatively low temperatures, would pose a further challenge to development of reliable wall heat transfer correlations. In addition, the lubricant may also vaporize and contaminate the discharge gas thus affecting the downstream process, unless the oil vapors are removed by using expensive filters. It is also not uncommon for cylinders and pistons to loose their concentricity because of poor lubrication, leading to operational failure and even irreparable damage to the components as a result of ceasing of the parts.

Finally from a designer and developers point of view, no amount of progress in analytical modeling or experimentation would help, unless quick and easy methods are developed for accurately predicting the discharge temperature, losses attributable to suction gas heating and its impact on volumetric efficiency and power economy. However, users of such methods should also be aware of their limitations, since reliable and accurate methods with universal applicability to all types of compressors are unlikely to be developed. Hence these analytical methods could only be used as tools for reducing the cycle time for development and one will have to rely on testing for proving the design.

CONCLUSIONS

In spite of the call by some researchers, as long as a quarter century ago, for the need to understand the influence of heat transfer and start modeling the phenomenon in reciprocating compressors, the author feels there is still some complacency about its importance. As implied in the article, it is perceived as a material technology problem and the main focus is aimed at developing new materials for improving component reliability. Hence serious effort appears to be lacking both at the fundamental level in understanding the mechanism enough to enable development of reliable heat transfer correlations and at the application level to enable development of easy, quick and reliable procedures for predicting its impact on compressor performance. It is only when the latter is achieved and demonstrated, compressor users can understand the seriousness of its impact and consequently demand the need for advancement in this area. Hence to this author, the ball appears to remain in the court of researchers to prove to the user community the need for work in this area.

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